

Stress analysis & life prediction of a cryogenic rocket engine thrust chamber considering low cycle fatigue, creep and thermal ratchetting

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Abstract

The paper deals with stress analysis, cyclic and creep life prediction of a cryogenic rocket engine thrust chamber, being used in one of the satellite launch vehicles of ISRO. The thrust chamber is of double walled construction wherein high conductivity copper alloy is used for the inner wall and stainless steel for the outer. Regenerative cooling of the chamber is achieved by passing the fuel through rectangular coolant passages milled on outer surface of the inner wall. The inner and outer walls are bonded together by brazing at high temperature. Failure of a double walled chamber occurs due to thinning of the inner wall and bulging into the chamber due to three mechanisms viz. (i) low cycle fatigue (ii) thermal ratchetting and (iii) creep. To capture the structural behaviour of the chamber in a complete sequence of operation of the engine, axisymmetric modeling and cyclic stress analysis is carried out using the ANSYS finite element analysis software package. High temperature mechanical properties, low cycle fatigue and creep properties of copper are characterised. Results of creep tests conducted at various temperatures are utilized for evaluating creep constants of Norton secondary creep model available in ANSYS. Analysis is performed in a seven load step sequence simulating one complete hot test of the engine. Life prediction is done using the cumulative damage accumulation methodology, considering the above three damage mechanisms. Allowable number of hot runs permissible is then arrived at after assigning suitable factors of safety for each damage mode.

1. Introduction

The engine is to develop a thrust of 75 kN in vacuum. The thrust chamber of this regeneratively cooled liquid rocket engine is of double walled construction with a nozzle exit area ratio of 1:200, overall configuration of which is shown in Fig. 1. A high conductivity copper alloy is used for the inner wall in regions of high heat flux whereas for other regions stainless steel is chosen. The outer wall is mostly of stainless steel.

2. Configuration of the thrust chamber

Regenerative cooling of the thrust chamber is achieved by passing the cryogenic fuel through rectangular coolant passages milled on outer surface of the inner wall. The outer and inner walls are bonded together by brazing at high temperature. The convergent and divergent subassemblies of this chamber are separately fabricated by brazing together the respective inner and outer walls. These subassemblies are subsequently joined together at the throat by welding the convergent and divergent inner walls initially and then the corresponding outer walls, thereby leaving the throat without any ribs. This renders the throat the most critical

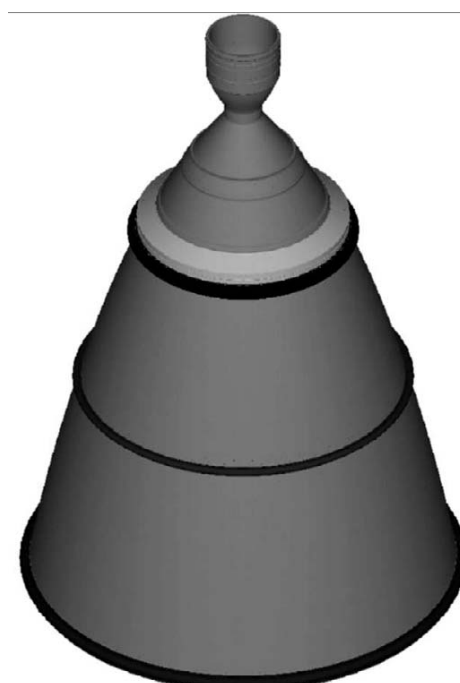


Fig. 1 : Configuration of thrust chamber

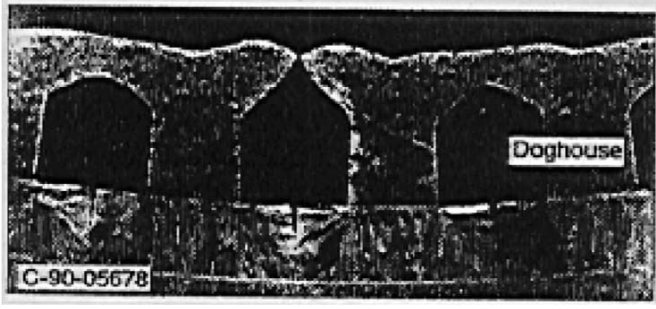


Fig. 2 : Mode of failure of a double walled thrust chamber

zone in the chamber since this weld zone coincides with the section of highest heat flux.

Failure of a double walled chamber occurs due to thinning of the inner wall and bulging into the chamber in a “dog-house” pattern due to three mechanisms viz. low cycle fatigue [1-5], cyclic accumulation of plastic strain during each hot run of the engine known as thermal ratchetting [6] and high temperature creep [7, 8]. Figure 2 shows the pattern of failure of a typical double walled thrust chamber [1] which is manifested as bulging of the inner wall inwards accompanied by wall thinning eventually leading to rupture of the mid channel region.

During each hot run of the engine the chamber walls have to withstand different combinations of thermal and pressure loads in a complete sequence of operation of starting and stopping transients, pre and post chilling operations, steady state operation etc. Figure 3 shows a cross section of the chamber which depicts these thermal and pressure loads.

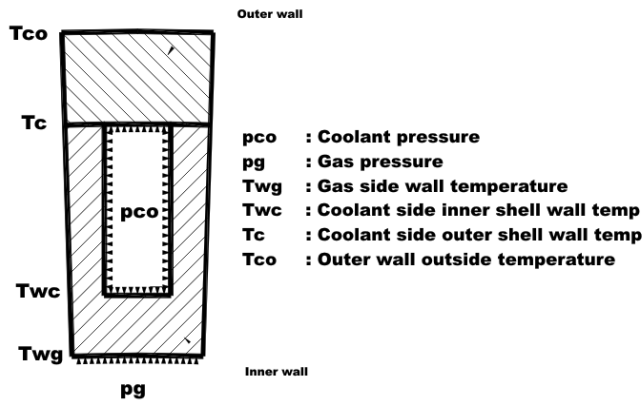


Fig. 3 : Details of double walled construction of chamber

3. Estimation of cumulative damage in the chamber

All the above three mechanisms contribute by varying degrees to the failure of the chamber. To sum up these effects, the damage caused by each mechanism is evaluated through an elasto-plastic geometric nonlinear finite element stress analysis using ANSYS. These damages are then summed up to get the total damage, the reciprocal of which gives the life of the chamber. The following sections outline the damage calculations:

3.1 Low cycle fatigue damage [4,5]

Damage due to LCF is simply the reciprocal of the number of cycles to fatigue failure is expressed as following:

$$D_{LCF} = \frac{1}{N_f} \quad (1)$$

where N_f = No. of cycles to fatigue failure at the highest operating temperature (which is obtained from the material $\Delta\epsilon$ -N curve) of the inner wall material.

3.2 Creep damage [7,8]

It is the ratio of time of actual operation to time to failure by creep at a particular stress level.

$$D_{creep} = \left(\frac{t}{t_r} \right)_{\sigma} \quad (2)$$

where t = actual time of operation at stress σ

3.3 Ratchetting damage [6]

It is the ratio of accumulated plastic tensile strain in a cycle to the fracture strain of the material.

$$D_{ratchetting} = \frac{\epsilon_{acc}}{\epsilon_f} \quad (3)$$

3.4 Cumulative damage [6]

The cumulative or total damage is the sum of the individual damage due to LCF, creep and ratchetting.

$$D_{total} = D_{LCF} + D_{creep} + D_{ratchetting} \quad (4)$$

The number of cycle to failure, N_f would be the reciprocal of the total damage.

$$N_f = \frac{1}{D_{total}} \quad (5)$$

4. Characterisation of chamber materials

In order to evaluate the effects of the above damage mechanism correctly, a material characterization program was carried out for different thrust chamber materials at high temperature.

4.1 Tensile tests

Mechanical properties viz. Young's modulus, yield strength, ultimate strength, percentage elongation and percentage reduction in area are evaluated for each specimen. Figure 4 and 5 give the complete stress-strain graphs up to fracture for copper alloy and stainless steel at 473 K respectively. Table 1 gives the details of specimens tested

Table 1 : Details of high temperature tensile tests

Material	Test temperatures (K)				
Copper alloy	300	473	673	873	1073
Stainless steel	“	“	“	“	“

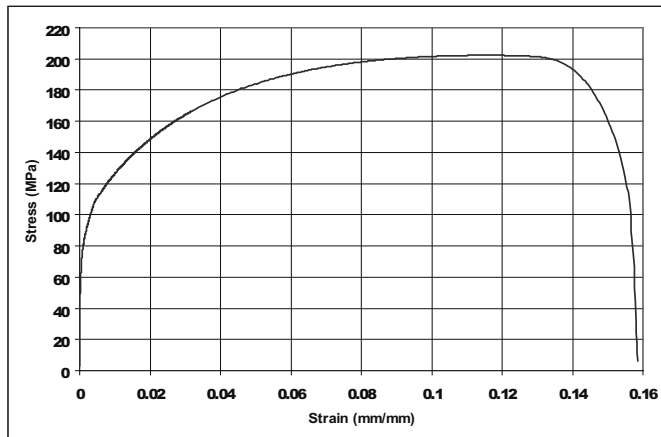


Fig. 4 : Stress strain graph for copper alloy at 473 K

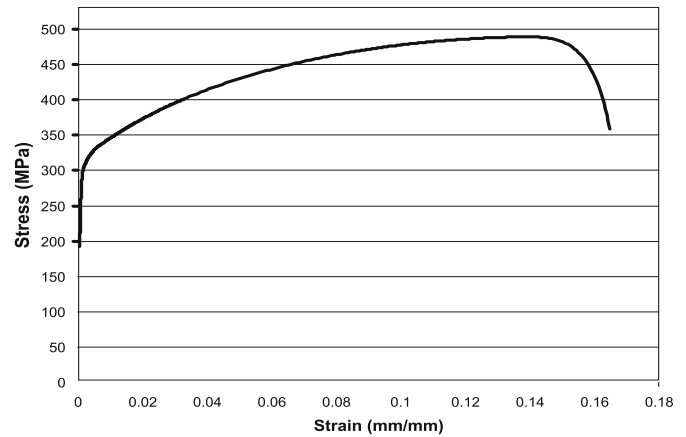


Fig. 5 : Stress strain graph for stainless steel at 473 K

at various temperatures, the number of specimens tested at each temperature being 3.

4.2. Creep tests

Constant load creep tests are conducted at temperatures ranging from 300 K to 1000 K for copper alloy and from 300 K to 875 K for stainless steel. Figure 6 shows the details of creep test specimens used for copper and stainless steel. Fig. 7 shows a typical creep curve of copper alloy whereas Fig. 8 gives that of stainless steel. Table 2 gives the number of copper alloy specimens tested for creep.

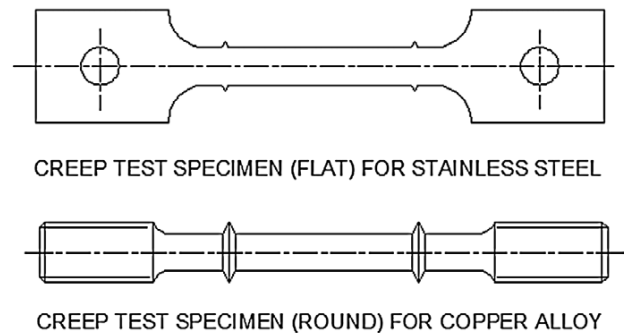


Fig. 6 : Creep test specimens

Table 2 : Details of creep tests done for copper alloy

Temperature (K)	Stress (N/mm ²)	No. of specimens tested	Temperature (K)	Stress (N/mm ²)	No. of specimens tested
300	275	2	873	80	1
	250	2		70	2
	200	2		65	2
	150	2		60	1
500	190	1	900	55	1
	175	2		50	1
	150	2		70	1
	100	2		60	4
700	155	2	950	55	3
	125	2		50	1
	100	2		45	1
	90	2	1000	50	2
800	95	1		45	3
	85	3		40	2
	70	1		30	2
823	80	1		25	2
	75	1		20	2
	70	3	Total	75	
848	95	1			
	80	3			
	75	2			
	70	3			
	60	1			
	45	1			

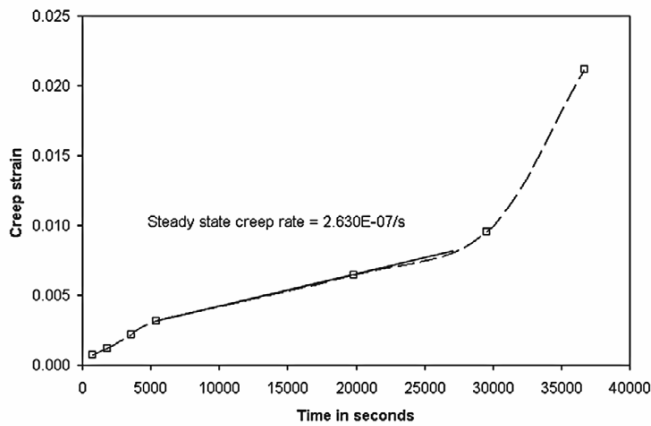


Fig. 7 : Creep test results for copper alloy

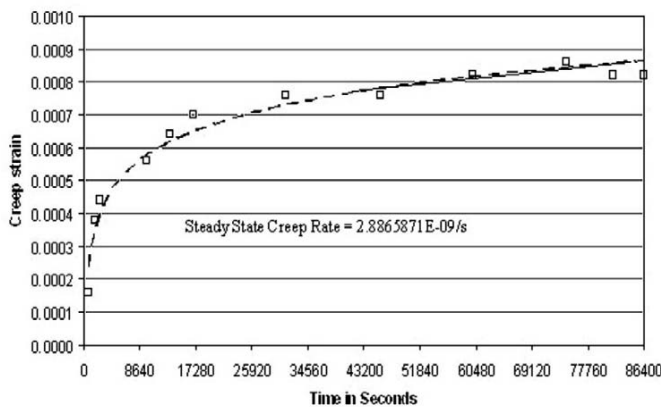


Fig. 8 : Creep test results for stainless steel

It is observed from the test data that primary and tertiary creep of the wall materials are negligible. Hence secondary creep only is considered. The Norton secondary creep model is used for creep modelling [10,11], given by:

$$\Delta \epsilon_{creep} = C_1 \sigma^{C_2} \exp \frac{-C_3}{T} \Delta t \quad (6)$$

It is found from the test results that the creep is not significant for stainless steel for the range of temperatures investigated. Hence creep phenomenon is not considered for this material.

4.3 Low cycle fatigue tests

Details of the number of specimens tested for LCF are given in Table 3. Figures 9 and 10 show the graphical representation of LCF test results for copper alloy and stainless steel respectively.

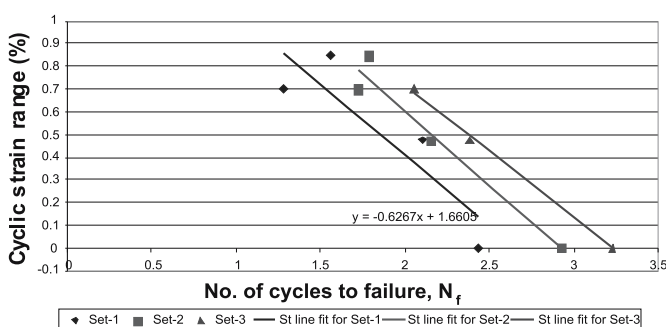


Fig. 9 : LCF test results for copper alloy at 873 K

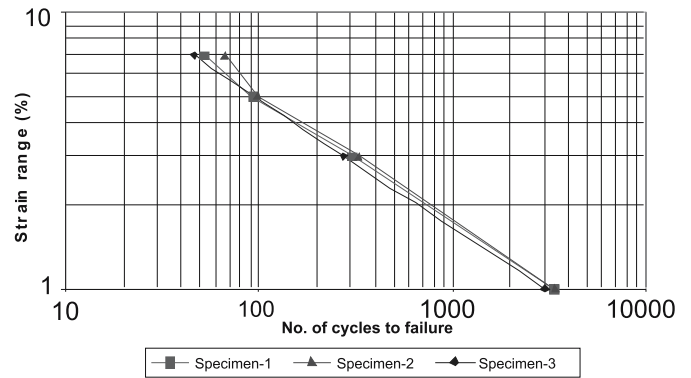


Fig. 10 : LCF test results for stainless steel at 873 K

Table 3 : Details of LCF tests

Material	Test temperature (K)	No. of specimens tested
Copper alloy	873	12
Stainless steel	873	12

5. Finite element modelling and stress analysis

Axisymmetric modelling of the chamber is found to be well suited for stress analysis of the overall chamber in general and cyclic life estimation of the throat region in particular. FE model of the main zone of the chamber up to an area ratio of 114 is generated using ANSYS [9]. Both the inner and outer walls are idealized as axisymmetric ones whereas the ribs are modelled using orthotropic material properties [12] since its stiffnesses in the radial, circumferential and meridional directions are different. Fig.11 shows the FE model details.

5.1 Orthotropic modelling of ribs

Ref. 12 gives the details of the axisymmetric modelling of a NASA test thrust chamber in which orthotropic properties have been used for idealization of the axial ribs of the chamber. The same methodology with the improvements as given below is adopted here to account for the helical nature of the ribs in the chamber.

The chamber is divided into different zones along its length having different rib and channel geometric properties. Orthotropic elastic properties are calculated based on the helix angles and the rib/channel geometries for each of these zones as a function of temperature.

5.2 Steady state thermal analysis

Peak surface temperatures for the inner and outer walls obtained from a separate thermal analysis are input for a steady state thermal conduction analysis to get the temperature distribution at all interior nodal points. PLANE77 elements are used to idealize the chamber. Using this temperature distribution at nodes, stress analysis of the model is conducted.

5.3 Elasto-plastic stress analysis

PLANE82 elements are used to build the model. Chamber and coolant pressures available all along the length of the chamber are input for stress analysis along with the above

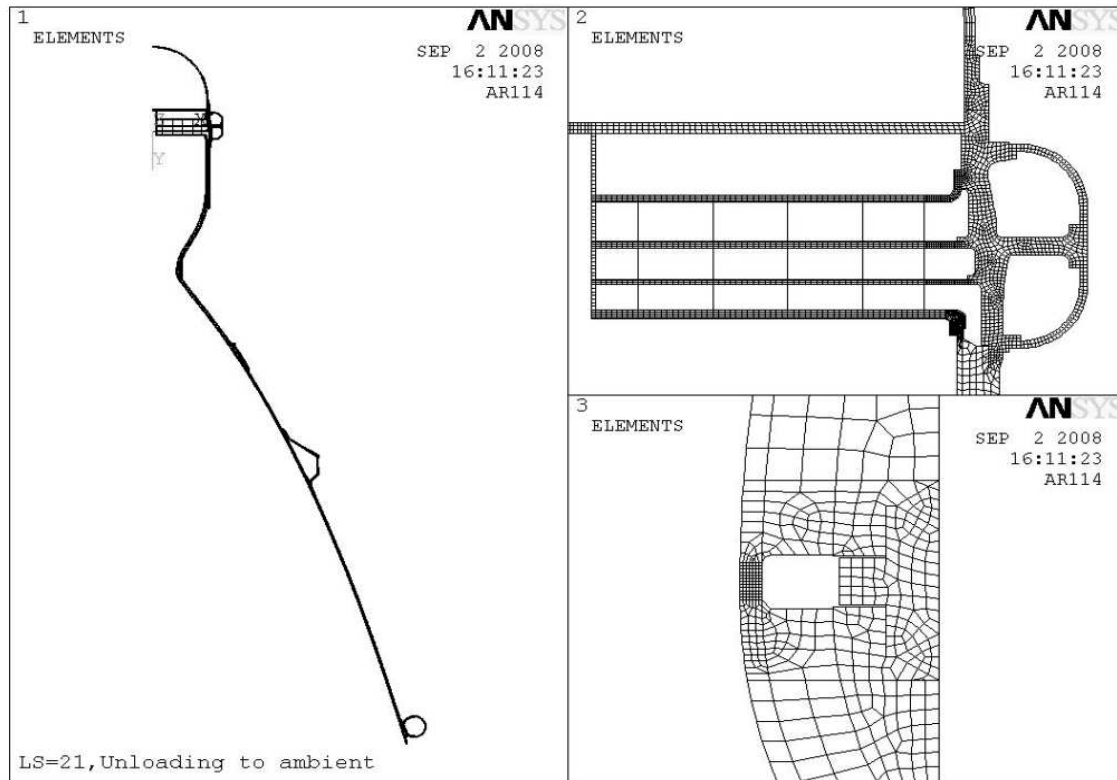


Fig. 11 : Finite Element model of thrust chamber

thermal loading. Bilinear kinematic hardening plasticity option is employed for constitutive modeling of inner and outer walls. Temperature dependent mechanical properties of copper alloy and stainless steel, obtained from the earlier experiments are input.

5.4 Creep analysis

Creep is incorporated in the analysis by invoking the Implicit Norton secondary creep model in ANSYS in conjunction with the above plasticity model for copper alloy. The sequence of application of various thermal and pressure loads on the chamber walls is shown in Table 4.

6. Results

Deformed shape at peak load during the first cycle of operation of the chamber is shown in figure 12 in which the

inward bulge of inner wall is very clearly seen at the throat. The meridional stress-strain curve for gas side mid throat region for 2 complete cycles of operation of the chamber is shown in Fig. 13. The stress strain characteristics for the second cycle are used for life prediction since the first loop is for a virgin chamber. The difference between the final strain values for the second and first cycles represents the incremental strain accumulated at the end of second cycle, i.e. ratchetting strain. Based on the assumption that fracture occurs in tensile mode only, positive strains are considered for ratchetting.

$$\text{Cyclic strain range, } \Delta \epsilon = 7.25\text{e-}3$$

$$\text{Ratchetting strain, } \epsilon_r = 1.35\text{e-}3$$

In this analysis, since both LCF and creep effects are considered in a combined fashion, damage due to both is given by:

$$D_{total} = 8 \times D_{LCF+creep} + 4 \times D_{ratchetting} \quad (7)$$

where a factor of safety of 4 is used for LCF and 2 for ratchetting and an additional factor of safety of 2 for both for the welded throat region [13]. Allowable number of hot tests of the thrust chamber is given by:

$$N_a = \frac{1}{D_{total}} \quad (8)$$

Table 4 : Details of loading sequence

Load step #	Thermal load	Pressure load	Description
1	150 K	0.2 MPa	Pre-start
2	150 K	$p_g + p_{co}$	Start of combustion
3	Steady state gradient	$p_g + p_{co}$	Steady state operation
4		$p_g + p_{co}$	Creep analysis for 720 sec
5		p_{co}	Combustion shutdown
6	150 K	p_{co}	Post-shutdown
7	Nil	Nil	Ambient condition

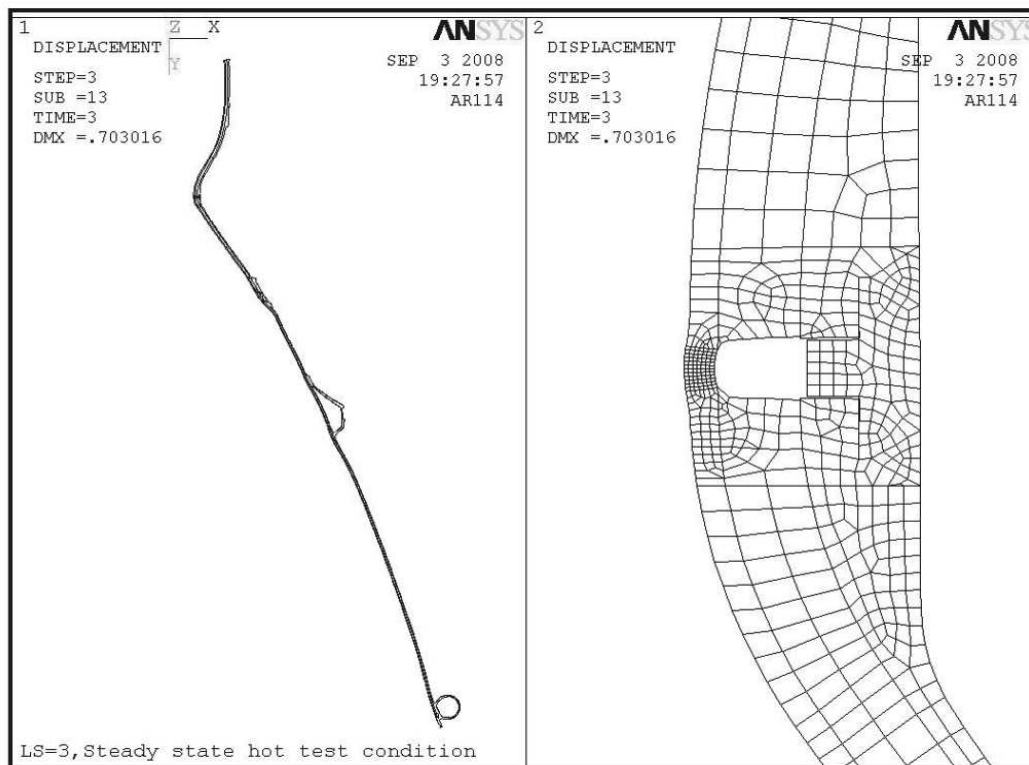


Fig. 12 : Deformed shape at peak load

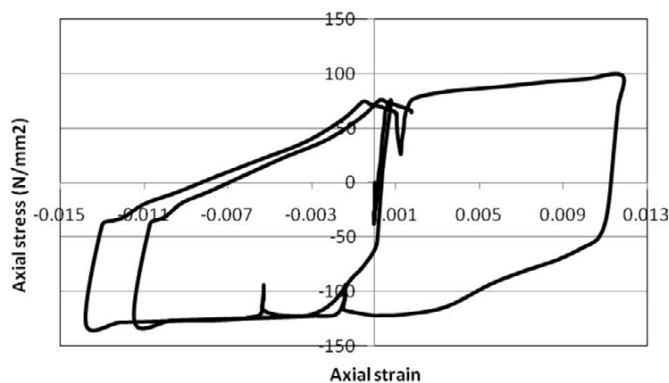


Fig. 13 : Cyclic axial stress strain curve at throat

7. Conclusion

In this paper, various material characterization testing, finite element modelling and stress analysis techniques for the double walled thrust chamber for a liquid rocket engine are discussed. The effect of various damage mechanisms are investigated for determining the number of hot tests permissible for the engine. It is found that the effect of creep is insignificant for stainless steel for the temperature range of interest. Low cycle fatigue is found to be most predominant failure mechanism for the copper alloy.

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